

MODELING COSMIC RAY ANISOTROPIES NEAR  $10^{18}$  eV  
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ABSTRACT

A galactic magnetic field reversal near the Sagittarius spiral arm may be responsible for the southern excess (or northern shortage) of cosmic rays near  $10^{18}$  eV. The north-south asymmetry produced by such a reversal would increase with energy in the same manner as the observed asymmetry [1,2]. The existence of a reversal has been inferred from analyses of Faraday rotation measures [3,4].

I. The puzzle. Cosmic ray fluxes in the EeV range ( $1 \text{ EeV} = 10^{18} \text{ eV}$ ) display a prominent anisotropy. The flux is suppressed at northern galactic latitudes, and the effect increases with energy through the decade .5-5 EeV [1,2]. This measured anisotropy should be instrumental in any attempt to piece together a picture of the Galaxy's magnetic field and the sources of high energy cosmic rays. Other pieces of this puzzle are the following:

1. The cosmic rays at this energy are probably mostly protons. This is based mainly on studies of the depth of maximum of air showers and the variance in the depths of maximum [5].

2. The mean galactic magnetic field near the sun has a magnitude of about  $2.2 \mu\text{G}$ , and at least near the sun it is directed clockwise about the galactic center as viewed from north of the Galaxy [6]. Protons moving perpendicular to the field lines have orbit diameters  $D = E$ , where  $E$  is the energy in EeV and  $D$  is in kpc. The energy decade .5-5 EeV therefore provides probes up to distances of 5 kpc.

3. The sources of these cosmic rays are probably galactic. By virtue of Liouville's theorem, the anisotropic observed flux cannot come from an isotropic extragalactic flux. If the extragalactic flux is not isotropic but is coming primarily from the Virgo cluster, then it is very difficult to explain how the anisotropy could be turned into a southern excess over a whole decade of energies. It is conceivable, though, that some of the cosmic rays in this energy decade are coming from the southern side of the Galaxy (rather than from the Virgo cluster). For example, acceleration by galactic wind termination shock [7] might occur between the Galaxy and the Magellanic clouds and could preferentially fill the southern half of an extended halo. If the ordered magnetic field were confined to a thin enough disk, then a southern excess would be expected as these particles diffuse northward. Any such model would be rather contrived, however, since it would require a southern source to be prominent only in a limited energy band where no remarkable spectral bump is observed. In the following we will assume that EeV cosmic rays are of galactic origin.

4. The magnitude of the disordered part of the galactic magnetic field is not much greater than the mean (ordered) field strength, even in dense clouds [8,9]. An abrupt large-angle change in a particle's direction is therefore rare. The scale of magnetic irregularities probably does not exceed 150 pc [10]. For EeV protons whose orbit circumferences are several kiloparsecs, the orbits therefore sense primarily the mean field but suffer frequent small deflections from magnetic irregularities.

5. The ordered galactic magnetic field is probably not confined to a thin disk, but may extend 3 kpc or more to either side of the plane. If the ordered field were confined to a thin disk of 1 kpc full thickness, for example, then at energies above 1 EeV no proton orbiting perpendicular to the field direction could be confined. At several EeV a pronounced excess would be detected from directions nearly parallel or anti-parallel to the field direction. Moreover, just below 1 EeV, protons orbiting perpendicular to the field lines would be confined only if their orbits met the galactic plane nearly perpendicularly. In particular, arrivals from the galactic center and anti-center directions would be strongly suppressed. In evaluating the thickness of the ordered magnetic field, it would be helpful to have not only the observed dependence of flux (at various energies) on the north-south variable (galactic latitude) but also the mean flux values projected onto the galactic center-anti-center axis as well as flux values projected onto the axis parallel to the mean field direction.

6. Analyses of Faraday rotation measures [3,4] suggest that a reversal of the ordered field occurs between the sun and the galactic center. Various estimates exist for the distance to the reversal, but a distance of 2 kpc may be realistic. Field reversals of this type are seen in other spiral galaxies (M51, M33, M81, NGC 6946, NGC 4258) [11,12]. Among the spiral galaxies whose fields have been mapped, M31 is exceptional in not showing a field reversal [13,14].

II. Assembling a picture. Putting together pieces 4 and 5 one finds that EeV cosmic rays are governed by a large-scale ordered magnetic field. In this context Hillas [15] has made the following cogent argument that a southern excess at Earth implies the existence of a radial gradient in the cosmic ray density: Liouville's theorem requires that the intensity (per unit area and solid angle) from the south at point P in figure 1 must equal the intensity from the north at earth. The observed southern excess at earth then implies that the intensity from the south at earth exceeds the intensity from the south at P. Similarly, the intensity from the north at Q exceeds the intensity from the north at earth. Therefore the northern and southern intensities increase with galactic radius. It can also be shown that if the density of cosmic ray orbit centers increases linearly with galactic radius near the sun, then the observed north-south asymmetry should increase linearly with energy (i.e. orbit size).

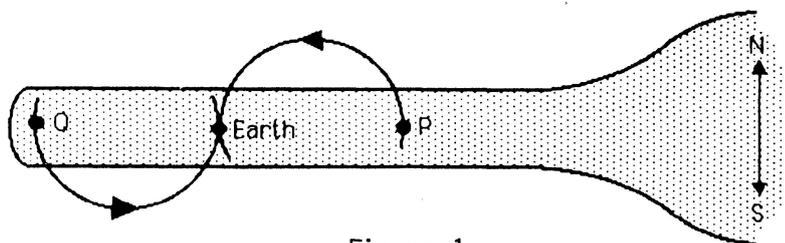


Figure 1

If the orbits shown in Hillas' figure are proton orbits at 4 EeV (where the southern excess is very prominent), then points P and Q are separated by 8 kpc. Even if one considers trajectories of median pitch angle, the inferred radial gradient persists over 4 kpc. A source density variation over such large distances would not be due simply to variation within or between spiral arms. We know of no reason why high energy cosmic ray sources should be more abundant at larger galactic radii.

If the cosmic ray density gradient is not due to a source gradient, then it must be due to some propagation effect. Instead of excess sources outside the sun's galactic orbit, one can look for a sink region closer to the galactic center. A field reversal region is an effective evacuation site for cosmic rays. Figure 2 shows some of the fast-escaping trajectories near a reversal. (The shaded regions are regions where  $\text{grad}|B| \neq 0$ .)

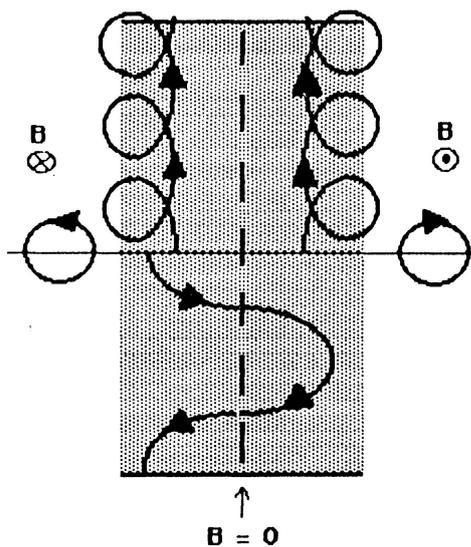


Figure 2

The field reversal zone is then a region of low cosmic ray density, so a density gradient points away from that region (radially outward at the sun's position). Orbits of very high energy cosmic rays could be affected directly by the field reversal, causing a pronounced shortage at high northern latitudes.

Our numerical simulations confirm that the energy dependence of the northern shortage (southern excess) can arise from a uniform source density if there is a field reversal at about 2 kpc with a gradient region of .5 kpc on either side of it and if there is some admixture of isotropic flux from the halo or intergalactic space.

III. Remarks. A definitive explanation for the northern shortage of EeV cosmic rays may not be possible without more detailed knowledge of the galactic magnetic field and cosmic ray sources. If careful analysis determines that the ordered magnetic field is, after all, confined to a thin disk, then a planar excess model [16] (i.e., shortage at north and

south poles) might be a complete explanation for the anisotropy. Or perhaps it will be found that a significant fraction of EeV cosmic rays are heavy nuclei, in which case a spiral arm source density gradient could be the correct explanation. In fact, each puzzle piece is rather fuzzy. In support of the field reversal explanation, we only claim that it is a picture which is composed of the pieces described above and which requires no special ad hoc pieces.

#### Acknowledgement.

This research was supported by the United States National Science Foundation under grant number PHY8415294.

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